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AIRBORNE TACTICAL CROSSLOAD PLANNER

by

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AIRBORNE TACTICAL CROSSLOAD PLANNER

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ABSTRACT

Planning airborne operations for a flight of aircraft to drop heavy equipment and paratroopers on a target dropzone is complicated. This thesis presents the Tactical Crossload Planner (TCP), an optimization-based decision support tool that rapidly devises a tactical crossload (a combination of paratroopers and equipment) to be loaded on multiple, heterogeneous aircraft for delivery in one or two low passes over a target dropzone. The optimization model captures an airborne commander's intent and best reflects priorities for the operation while meeting detailed operational requirements set out in the Airborne Standard Operating Procedure (ASOP).

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LIST OF ACRONYMS AND ABBREVIATIONS

AA	assembly area
ABN	airborne
AFAR	Airborne Field Artillery Regiment
AGL	above ground level
AO	area of operation
APA	American psychological association
ASOP	airborne standard operating procedure
A/C	aircraft
BCT	brigade combat team
BN	battalion
CSV	comma-separated value format
HEPI	heavy equipment point of impact
JFEX	joint forcible entry exercise
JM	jumpmaster
PAX	personnel and equipment
POI	point of impact
PVL	priority vehicle list
ME	main effort
RAP	ranger air load planner
SE	supporting effort
SOP	standard operating procedure
TCP	tactical crossload planner
USSOCOM	Unites States Special Operations Command

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EXECUTIVE SUMMARY

The United States Army's capability to forcibly insert paratroopers to any location across the world in a matter of hours is a key aspect of our military posture. The planning of airborne operations to provide this ability is exacting. This thesis presents an optimization-based decision support tool that offers a tactical crossload (a combination of air-dropped equipment and paratroopers) assigning equipment items and paratroopers to individual, heterogeneous aircraft so they can be dropped in one or two low passes over a target drop zone.

An airborne mission is led by an Airborne Commander and consists of several sub-missions that facilitate the overall accomplishment of the airborne mission. These sub-missions are led by subordinate commanders responsible for their own independent objectives. These sub-objectives are often scattered across the dropzone and the time it takes to assemble the sub-mission personnel can be significant if paratroopers exiting their aircraft land in dispersed locations. Once on the ground, time is critical; paratroopers are highly susceptible to counter-attacks because of their relatively light armaments. Speedy assembly of each sub-mission's personnel is critical to the success of the airborne mission.

The tactical crossload specifies for each aircraft assigned to the airborne operation which seat positions will be occupied by air-dropped heavy equipment or paratroopers assigned to particular sub-missions. These seat assignments govern when paratroopers exit the aircraft in relation to the drop zone and, subsequently, how close they land to their respective sub-mission locations.

In this thesis, we formulate and implement an integer linear program called the Tactical Crossload Planner (TCP) that takes inputs from the Airborne Commander, subordinate commanders, and the airborne planners to create a complete tactical crossload. The maximized objective evaluates the desirability of a tactical crossload in terms of the Airborne Commander's intent and penalizes failure to meet any desired crossload objectives.

We demonstrate TCP with two real-world tactical problems from recent airborne operations: one by the 4-319th Airborne Field Artillery Regiment (AFAR) and another by the 173 Airborne Brigade Combat Team (BCT). The former problem involves two aircraft, two pieces of air-dropped equipment, and between 107 and 111 paratroopers, while the latter has twelve aircraft, and 555 paratroopers. TCP creates feasible solutions to each of the airborne operations that are essentially indistinguishable from the original, actual manual tactical crossload.

There are three significant benefits of the TCP. One is its speed; the TCP produces a tactical crossload in a fraction of a second. While it does require forethought and planning to enter the inputs required by TCP, its response is essentially instantaneous compared with the current time required to manually devise a tactical crossload. TCP addresses the most time-demanding aspects of creating the tactical crossload, the scatter plan (dispersion plan), and automates it. This frees the Airborne Commander and subordinate commanders to focus on planning ground operations. The second benefit is the flexibility the tool provides. Often the set of aircraft planned for is not the set that arrives at load time. This could be due to, for instance, mechanical aircraft casualties. The available aircraft may have different configurations (numbers of seats) than originally anticipated. In response to such a surprise, a “bump” plan is hastily initiated, the quality of which varies across organizations. However, even a good, hasty bump plan probably cannot take scatter into account effectively. With TCP, a planner can change the available aircraft or their configurations and have a new tactical crossload in moments. Finally, using a tool like TCP requires that the Airborne Commander and subordinates clearly express their intent through the TCP input, and this provides, at once, a level playing field for planners as well as an objective record of the rationale behind the resulting crossload plan.

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I. INTRODUCTION

A. BACKGROUND

The United States Army airborne capability is a critical component of the United States' ability to project force around the world. The capability to forcibly insert paratroopers wherever and whenever necessary is a key aspect of the United States' military posture. This enables the United States to reach out and put boots on the ground, with little to no notice, in strategically important areas.

Manually planning these operations is extremely exacting and time-critical. A planning staff can struggle to determine the size of the force required to accomplish a given mission. The size of an airborne mission is determined not only in terms of personnel and their personal equipment (PAX), but also in terms of heavy items of equipment, vehicles, or artillery pieces that are dropped as part of an airborne operation. The detail required for a single airborne operation can challenge any planning staff.

A basic airborne plan is centered on a single airborne mission, led by the Airborne Commander, with several sub-missions required to achieve the overarching, airborne mission, each led by a subordinate commander. To provide the planning needed for an airborne operation there are either dedicated airborne planners or staff sections assigned the extra duty of airborne planning. This will vary based on the echelon (e.g. Brigade, Battalion, or etc.) of the unit leading the airborne mission.

The additional detail included in airborne operations comes from the multiple sub-missions necessary to accomplish the overall airborne mission. These sub-missions are spread across the intended *dropzone*, which presents the question of how to best enable each paratrooper to accomplish an individually assigned mission. In time-sensitive airborne operations, enabling speedy assembly after landing is crucial.

From the need to achieve speedy assembly comes the *tactical crossload*: the positioning of personnel and equipment strategically within and across aircraft to minimize the distance a paratrooper has to traverse on the ground to reach an assigned assembly area. Given the intended azimuth of approach of aircraft over a dropzone, their speed, parallel track offsets, and altitude to avoid ground obstacles, all external inputs from the Air Force, a successful crossload plan considers multiple aircraft, multiple sub-missions, PAX, heavy items of equipment, and the safety regulations set out in the Airborne Standard Operating Procedure (ASOP 2011). The tactical crossload specifies for each aircraft the seat positions to be occupied by heavy equipment or paratroopers assigned to particular sub-missions.

The foundation of any tactical crossload is the *chalk*. Each aircraft has two chalks, one for each paratroop door (used to exit the aircraft while in flight), which will consist of PAX from multiple sub-missions. Each chalk is then broken down to individual seat assignments; this attempts to forecast and control the dispersion of paratrooper landings across the drop zone.

Planners must incorporate the Airborne Commander's intent in the disposition of personnel and heavy items of equipment, across the multiple sub-missions, in limited aircraft space. The task of managing the variety of demands across all the sub-missions to facilitate a successful airborne operation is daunting. Unfortunately, the creation of a tactical crossload plan is not the primary duty of the Air Officer or Non-Commissioned Officer at the Battalion level and below. This often means that a tactical crossload plan is not given the attention it might deserve at the experience level necessary. Therefore, it benefits the entire airborne community to build a tool that can facilitate the *efficient* creation of the load plan and manifests (outputs of the tactical crossload), while meeting the Airborne Commander's intent.

Planners face additional complications, such as frequent aircraft mechanical casualties that unpredictably ground aircraft or the arrival of different numbers of aircraft, or aircraft of differing configurations than anticipated prior to planning. Such events force commanders to make last-minute changes. If an aircraft goes down, standard procedure includes a *bump plan*; however, if that bump plan is in place, it would almost certainly not include an updated crossload. The airborne community can benefit from a planning tool that can quickly create a bump plan that seamlessly adjusts to the available aircraft.

The Ranger Air Load Planner (RAP) (Moore 2000) was created for United States Special Operations Command (USSOCOM), specifically the 75th Ranger Regiment, to enable the creation of automated, optimized, load plans based on pre-approved templates. RAP, though, only focuses on the most efficient loading of equipment (i.e., fitting the largest amount of equipment across a fleet of aircraft), and takes no account of PAX or airborne operations.

B. AN AIRBORNE MISSION

The U.S. airborne community conducts hundreds of missions every year. Planning a mission can place great demand on the respective organizations and varies greatly in difficulty depending on the size and scale of the specific mission. Planners involved can range from two to three people for a couple of hours, to teams numbering in the dozens for weeks. The approximate timeline produces only a single plan that does not consider potential adjustments or bump plans that may arise due to complications, including the failure or substitution of any of the aircraft.

Two parallel chalks of paratroopers descending to the ground from a departing aircraft. U.S. Army photo taken on February 28, 2013, by Sgt. Michael J. MacLeod. Accessed May 1, 2017, https://www.army.mil/article/97377/Mass_tactical_Airborne_Operation.

Figure 1. Airborne Operation Employing Two Aircraft February 2013.

The success of any airborne mission hinges on surprise. The Army manual on operations defines surprise as, “strik[ing] at a time or place or in a manner for which the enemy is unprepared.”(ADRP 3-0 2016) An airborne operation has one unique, crucial element that enables surprise: the method of delivery for the paratroopers to the objective. Surprise works in an airborne operation in many ways. The first key event on an airborne timeline is the arrival of the paratroopers and heavy equipment at the departure airfield. Upon arrival the paratroopers are split into their chalks and given their first opportunity, as a chalk, to rehearse the airborne component of the operation together. After rehearsing for approximately an hour each paratrooper will don a parachute and equipment and wait to board the aircraft. While this is taking place, the heavy items of equipment are rigged and loaded into their assigned aircraft. After the heavy items of equipment are loaded the paratroopers will then load and await take-off and flight to the dropzone. The aircraft with all the necessary elements of surprise then fly to the objective (ASOP 2011).

Upon approaching the dropzone, the element of surprise gives way to the principal of speed. The aircraft carrying heavy equipment are first to cross the dropzone, dropping the heavy equipment items. Following these aircraft are the PAX-pure aircraft, those carrying only PAX. The PAX-pure aircraft drop their paratroopers, while the heavy equipment aircraft circle. Finally, the heavy drop aircraft return to drop their PAX. Even after exiting the aircraft at the maximum drop height, each paratrooper has mere seconds to maneuver a parachute before landing. Upon landing, each paratrooper makes way to an assigned sub-mission Assembly Area (AA). Once an AA reaches the manning requirement for its associated sub-mission, the element assembled there will immediately initiate movement in route to their sub-mission. It is only with the accomplishment of all the sub-missions that the overall objective can be accomplished. Paratroopers must move as fast as possible to accomplish their objective before a counter-attack arrives.

The importance of speed cannot be overstated, and speed is highly emphasized throughout the airborne planning process. Speed is primarily addressed in the *scatter plan*, the portion of the tactical crossload that addresses the dispersion of paratroopers. The scatter plan is a critical part of the tactical crossload, organizing the chalks and paratroopers within the chalk in such a way that each paratrooper lands as close as possible to the assigned AA to facilitate a speedy assembly. Facilitating speedy assembly is not only critical to success, but also presents significant demands in terms of the time required to create the tactical crossload.

Airborne operations have the advantage of surprise; however, they also have an inherent weakness in the necessity to travel light. The Army uses three types of Brigade Combat Teams (BCTs): Light, Stryker, and Heavy. The airborne community consists entirely of Light BCTs because only relatively light pieces of equipment are air droppable *and* survivable. For example, an airborne unit does not possess tanks because they cannot be dropped from an aircraft and survive. The light composition of airborne units leaves them vulnerable to an inevitable counter-attack. Unarmored vehicles and the dismounted infantry of an airborne unit are at serious disadvantage when confronting a more numerous and potentially heavy or mechanized force.

Looking aft at paratroopers from 2BCT 82nd ABN DIV loaded in a C-17with a Humvee and M998 Howitzer. U.S. Army photo taken April 13, 2013, by Sgt. Joseph Guenther. Accessed April 13, 2017, https://www.army.mil/article/101038

Figure 2. C-17 Loaded with Paratroopers and Heavy Equipment

One standard objective carried out by paratroopers is to secure an airfield to facilitate the establishment of a heavier following force, which, in most scenarios, consists of armored follow-on assets. These follow-on assets will generally come via Airland Operations that require a secure airfield, which are facilitated by the accomplishment of most, if not all, of the sub-missions of the airborne mission (Hershman 2005).

C. CURRENT PRACTICE

There is currently no set standard for planning airborne operations. Rather, there are common practices within each airborne unit regarding when, where, and who takes part in the planning. In its current form, planning takes a significant amount of time from several select individuals, who may not develop an optimal solution from the perspective of the Airborne Commander. This potential failure can derive from restrictions on the Airborne Commander's time, as well as the Commander's inability to take part in all aspects of complete planning process.

There are some base planning considerations that govern every airborne operational planning session. When an airborne mission is assigned, the respective planning team will determine the number of the sub-missions required to achieve the assigned mission. The staff in coordination with the Airborne Commander and the subordinate commanders will then determine the planned composition of the sub-missions. This composition will consist of both personnel and heavy equipment. The heavy equipment is consolidated into a Priority Vehicle List (PVL) at the echelon of the Airborne Commander. At this point, the Airborne Commander requests planes from the Air Force capable of supporting the desired number of personnel and pieces of heavy equipment. Based on the response from the Air Force, the composition of the airborne operation will be adjusted to maximize the capabilities of the aircraft available (ASOP 2011).

After the Air Force has assigned aircraft to the mission, the tactical crossload will begin to take shape. How the crossload is determined has no set form and will proceed based on the organization and the size and scope of the operation. Given the guidance issued by the Airborne Commander, the planners will begin to adjust the composition of the airborne operation based upon the available aircraft. Priority of each sub-mission is assigned based on that sub-mission's influence on the success of the overall mission. This priority then influences the assets the Airborne Commander will allocate to the particular sub-mission.

After the composition of each sub-mission has been decided, the hard work of assigning seats against each sub-mission begins. There are several considerations when assigning seats; first is the scatter plan and how long it will take each sub-mission to assemble at its respective AA. There are several methods that can be used to achieve this; for example, restricting the number of PAX of each sub-mission permitted on each aircraft, or limiting the number of sub-missions on each aircraft. Second, several other determinations must be made, such as the assignment of a minimum of two jumpmasters per aircraft (ASOP 2011).

Paratroopers exit C-17 in-flight. Jumping jumpmaster, a paratrooper, a safety (non-jumping jumpmaster), jumper, and loadmaster (from the right) U.S. Army photo taken on June 21, 2014, by Staff Sgt. Jason Hull. Accessed May 22, 2017, http://www.flickriver.com/photos/82ndairbornedivision/14498050752/.

Figure 3. Paratroopers Exiting a C-17

The final consideration is the experience level of the jumpers. A guideline among the airborne community is to separate novice jumpers, those with less than 10 jumps, by placing more-experienced jumpers in between them to limit the number of consecutive novice jumpers exiting the aircraft (Pasquale 2017). This is a safety consideration to minimize both the risk from novice jumper's lack of experience, as well as the increased risk when novices appear sequentially in a chalk. The most important safety aspect of a jump is the exit. A paratrooper exits an aircraft at a relatively low altitude, which gives little to no time to fix any problems. A majority of problems in a jump arise from a poor exit: an exit lacking a ninety degree turn to square with the direction of flight and/or a vigorous jump out the door. The most common risk associated with a novice jumper is rushing the door, and failure to make the proper ninety degree turn before exiting. Sequentially placed novice jumpers compound this risk. Therefore, it is critical to monitor each exit carefully. Ideally there is a one-second interval between jumpers within the same chalk and a half-second interval between the two paratroop doors. However, rushing the door alters both the interval between the jumpers within the chalk and between the two paratroop doors. Another common problem experienced by a novice jumper, caused predominately by a poor exit, is twists in parachute risers, the cords that connect the paratrooper to a parachute canopy. Twists limit the size of the canopy a parachute creates and increase the rate of descent. A more experienced jumper will approach the door and maintain a proper interval, ensuring a proper exit. By interspersing the more-experienced jumpers among the novice ones, the tactical crossload can mitigate the risk associated with novice jumpers.

Regardless of the amount of time and effort invested to create a tactical crossload, there are several events that can, and frequently do, make the plan infeasible. For example, aircraft may arrive that are different in number or configuration than originally anticipated, or a mechanical failure may ground an aircraft. Currently, key personnel are designated for the well thought-out and rehearsed plans; in the event of changes in aircraft availability or configurations, those key personnel are moved to operational aircraft by randomly replacing non-key personnel. A revision like this does not take into account the new location of these key personnel within the scatter plan. This yields significant problems, such as the potential loss of critical personnel or equipment within sub-missions. Additionally, those non-key personnel removed may have critical roles or carry significant equipment for a respective sub-mission.

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II. DATA

A. DATA REQUIREMENTS

This thesis requires three sources of data: the Airborne Commander, subordinate commanders, and the airborne planners. The ability to combine these unique perspectives efficiently and unambiguously is the strength of this thesis.

An airborne planner is responsible for aircraft-specific information, the number of aircraft by type, and seats available per aircraft. In addition to collecting the aircraft information, an airborne planner is responsible for consolidating the PVL and detailing the specifics of each of the pieces of heavy equipment and the seat-equivalents it will occupy. Additionally, the airborne planners are responsible for a series of data requirements that influence the scatter plan and, subsequently, the speed of assembly. Data requirements include: the minimum and maximum number of paratroopers from a single sub-mission that can be assigned to a single aircraft, the minimum and maximum number of sub-missions that can be assigned to a single aircraft, and the maximum number of aircraft between which a sub-mission can be spread.

The Airborne Commander, potentially in conjunction with subordinate commanders, determines a minimum, maximum, and planned number of paratroopers associated with each sub-mission. This determination is made by the Airborne Commander expressing priority among the sub-missions, and also prioritizing each piece of heavy equipment.

Subordinate commanders have very little input into TCP because their influence comes mostly after the creation of the tactical crossload. The data required from the subordinate commanders is the allocation of novice jumpers, experienced jumpers, and jumpmasters against the planned number of paratroopers so TCP can create the tactical crossload.

B. LOAD TEMPLATES

TCP data consists of an EXCEL spreadsheet from which extracts define index sets, giving the dimensions of the model and names of its entities, and four files associating data with these dimensions. There are five index set files and four data files expressed in ‘comma-separated-value’ (csv) format. These files can be grouped into three themes: aircraft, PAX, and heavy items of equipment, which are used together to instantiate a TCP optimization model.

Aircraft tail numbers (identification) are found in a file called a.SET, and aircraft data, consisting of the number of seats available, for these tail numbers is in the file aircraft_data.csv (see Figure 4).

C_130J_1
C_130J_2
C_130J_3
C_130J_4
C_130H_1
C_130H_2
C_130H_3
C_130H_4
C_130H_5
C_130H_6
C_130H_7
C_130H_8

	A	B
1	a	seats
2	C_130J_1	55
3	C_130J_2	56
4	C_130J_3	55
5	C_130J_4	55
6	C_130H_1	41
7	C_130H_2	41
8	C_130H_3	42
9	C_130H_4	42
10	C_130H_5	42
11	C_130H_6	42
12	C_130H_7	42
13	C_130H_8	42

a.SET and aircraft_data.csv files (from left to right). “C_130J-1” has 55 seats.

Figure 4. Aircraft Data Inputs

Sub-mission indexes (names) are found in m.SET. PAX-related data is in planned_data.csv and mission_data.csv. Mission pairs that are mutually exclusive are listed in MEX.SET (see Figure 5). Planned_data.csv gives a breakdown by sub-mission of the size and composition (skill level) of each sub-mission. Mission_data.csv is set up for the Airborne Commander to express priorities in terms of minimum and maximum PAX numbers in the event planned aircraft do not arrive.

```
m01
m02
m03
m04
m05
m06
m07
m08
heavy
```

```
m02, m07
m03, m08
```

m	b	planned_pax
m01	novice	80
m01	experien	130
m01	master	17
m02	novice	2
m02	experien	6
m02	master	0
m03	novice	6
m03	experien	10
m03	master	1
m04	novice	70
m04	experien	130
m04	master	13

m	seq	min_pax	max_pax	pax_pri_l	pax_pri_up
m01	1	200	250	2	1
m02	2	5	12	2	1
m03	3	12	22	2	1
m04	4	200	225	2	1
m05	5	3	12	2	1
m06	6	20	35	2	1
m07	7	30	50	2	1
m08	8	12	25	2	1

m.SET, and MEX.SET, Planned_data.csv, mission_data.csv, files (from left to right) from Lift 2 of 173rd ABN BCT. Mission "m01" is planned for 80 novice jumpers, 130 experienced jumpers, and 17 jumpmasters. This mission is the first in chalk sequence and may have the total number of parachutists assigned vary between 200 and 250. The next two priorities are penalties in case this minimum or maximum must be violated, respectively. Missions "m02" and "m07" are mutually exclusive – equipment and/or jumpers assigned to these missions cannot be loaded on the same aircraft.

Figure 5. PAX Data Inputs

q.SET gives the indexes (identification) of heavy equipment items, and qm.SET associates each equipment item with a sub-mission. The file heavy_data.csv gives a priority (a reward) for loading each piece of equipment, and the number of seat positions that the equipment occupies. (See Figure 6.)

```
M119_Howitzer_1
M119_Howitzer_2
```

```
* q, m
M119_Howitzer_1 , m04
M119_Howitzer_2 , m09
```

q	equip_pri	seat_req
M119_Howitzer_1	100	12
M119_Howitzer_2	200	12

Heavy_data.csv, q.SET, and qm.SET (from left to right). The piece of equipment "M119_Howitzer_1" is associated with sub-mission "m04," has priority 100 and requires 12 seat positions on an aircraft.

Figure 6. Heavy Item of Equipment Data Inputs

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III. TACTICAL CROSSLOAD PLANNER

A. MODEL OVERVIEW

We present the TCP mixed-integer linear program that yields a feasible tactical crossload with the highest achievable total reward. The reward objective expresses the commander's priority (utility) for personnel and equipment leaving the aircraft, less penalties for unavoidable violations of planning goals.

The model has been implemented using General Algebraic System (GAMS, 2015). GAMS, in turn, can use any of a suite of optimization packages—here, we use CPLEX (IBM ILOG CPLEX, 2010). The per-seat cost of this software is approximately $6,000. TCP has also been implemented in PYTHON (Python Software Foundation, 2016), its mathematical modeling language PYOMO (Hart et al. 2012) and its spreadsheet interface package PANDAS (McKinney 2010), and solved with the optimization package GLPK (Makhorin 2012). PYTHON, PYOMO, PANDAS and GLPK are free, open-source systems.

B. INPUTS

1. Airborne Commander

(i) minimum, planned and maximum number of paratroopers to be assigned for each sub-mission
(ii) minimum, planned and maximum number of pieces of heavy equipment to be assigned
(iii) minimum and maximum number of sub-missions assigned to each aircraft
(iv) minimum and maximum number of paratroopers from a single sub-mission assigned to each aircraft
(v) maximum number of aircraft a sub-mission can be spread between

2. Subordinate Commanders

(i) planned number of paratroopers broken down by experience level (novice, experienced and/or jumpmaster)

3. Airborne Planner

(i) aircraft numbers, types, and seats available on each

(ii) pieces of heavy equipment (item label, priority, and seat requirement)

C. FORMULATION

1. Index Use [~cardinality]

$a \in A$	aircraft (C-130H, C-130J, C-17) [~10]
$m \in M$	missions (alias $m1$, $m2$) [~10]
$\{m1, m2\} \in MEX$	pairs of missions mutually exclusive on any aircraft
$q \in Q$	heavy items of equipment [~8]
$m_q \in M$	mission of equipment item q
$b \in B$	backgrounds for jumpers (inexperienced <10 jumps, experienced >=10 jumps, jumpmaster) (alias b')
$v \in V \subseteq B$	veteran numbers (i.e., experienced jumpers and jumpmasters)

2. Data

$seats_a$	seats available on aircraft a (two seats deducted for non-jumping jumpmaster; zero ➔ bumped)
min_pax_m	minimum number of jumpers allowed for mission m
$planned\_pax_{m,b}$	routine number of jumpers trained for mission m with background b
max_pax_m	maximum number of jumpers allowed for mission m
$pool_b$	jumpers with background b not assigned a mission
$\underline{pax\_pri}_m, \overline{pax\_pri}_m$	priority per jumper added to minimum number required by mission m, up to routine number, and per jumper added more than routine, but less than maximum jumpers ($\underline{pax\_pri}_m > \overline{pax\_pri}_m$)
seq_m	sequence of mission from lead edge of the drop zone [ordinal]
$\underline{assign}, \overline{assign}$	minimum, maximum jumpers from a mission who can be assigned to any aircraft (e.g., 3, 15)
$\overline{acpermission}$	maximum number of aircraft that can be assigned any mission
min_hvy	minimum number of heavy equipment items to load
$planned\_hvy$	routine number of heavy equipment items to load

max_hvy maximum number of heavy equipment items to load

$reward4assigns$ reward for number of missions assigned across all aircraft loads

$equip\_pri_q$ commander's priority for units of equipment item q

$seat\_req_q$ seats occupied by heavy item (1, 2, …)

$\underline{hvy\_pri}, \overline{hvy\_pri}$ priority per unit of equipment lower than planned units with at least minimum units remaining, and in addition to planned units, but not more than maximum units $\underline{hvy\_pri} > \overline{hvy\_pri}$

3. Decision Variables

$ASSIGN_{m,a}$ assign mission m to aircraft a [binary]

$HVY_{q,a}$ heavy equipment q loaded on aircraft a [binary]

$PAX_{m,b,a}$ number of jumpers for mission m with background b loaded on aircraft a [integer]

$DOWN\_PAX_{m,b}$ jumpers removed from routine number for mission m with background b

$ADD\_PAX_{m,b}$ jumpers added above routine number required for mission m background b

$EXCESS\_PAX_{m,b}$ jumpers in excess of maximum required for mission m with background b

$DOWN\_HVY$ heavy equipment units jumpers removed from routine number

ADD_HVY number of heavy equipment units added above routine number

$EXCESS\_HVY$ number of heavy equipment units loaded in excess of maximum

4. Objective Function and Constraint

$$
\begin{aligned}
\max \quad & +reward4assigns \sum_{\substack{m \in M, \\ a \in A}} ASSIGN_{m,a} \\
& - \sum_{\substack{m \in M, \\ b \in B}} \underline{pax\_pri}_m DOWN\_PAX_{m,b} + \sum_{\substack{m \in M, \\ b \in B}} \overline{pax\_pri}_m ADD\_PAX_{m,b} \\
& + \sum_{\substack{q \in Q, \\ a \in A}} equip\_pri_q HVY_{q,a} \\
& - \underline{hvy\_pri} * DOWN\_HVY + \overline{hvy\_pri} * \mathrm{ADD}\_HVY && \text{(J0)}
\end{aligned}
$$

$$
\begin{aligned}
\text{s.t.} \quad & \sum_{a \in A} HVY_{q,a} \le 1 && \forall q \in Q && \text{(J1)} \\
& \sum_{\substack{q \in Q, \\ a \in A}} HVY_{q,a} \overset{\circ}{=} planned\_hvy - DOWN\_HVY + ADD\_HVY + EXCESS\_HVY && && \text{(J2)} \\
& \sum_{a \in A} ASSIGN_{m,\mathrm{a}} \le \overrightarrow{acpermission} && \forall m \in M && \text{(J3)} \\
& HVY_{q,a} \le ASSIGN_{m_q,a} && \forall q \in Q, a \in A && \text{(J4)} \\
& ASSIGN_{m1,a} + ASSIGN_{m2,a} \le 1 && \forall a \in A, \{m1, m2\} \in MEX && \text{(J5)} \\
& \sum_{q \in Q} seat\_req_q HVY_{q,a} + \sum_{\substack{m \in M, \\ b \in B}} PAX_{m,b,a} \le seats_a && \forall a \in A && \text{(J6)} \\
& PAX_{m,b,a} \le \min(seats_a, max\_pax_m) ASSIGN_{m,a} && \forall m \in M, b \in B, a \in A && \text{(J7)} \\
& \sum_{b \in B} PAX_{m,b,a} \le \overline{assign} ASSIGN_{m,a} && \forall m \in M, a \in A && \text{(J8)} \\
& \sum_{b \in B} PAX_{m,b,a} \overset{\circ}{\ge} \underline{assign} ASSIGN_{m,a} && \forall m \in M, a \in A && \text{(J9)} \\
& \sum_{a \in A} PAX_{m,b,a} \overset{\circ}{=} planned\_pax_{m,b} - DOWN\_PAX_{m,b} + ADD\_PAX_{m,b} + EXCESS\_PAX_{m,b} \\
& && \forall m \in M, b \in B && \text{(J10)} \\
& \sum_{b \in B} DOWN\_PAX_{m,b} \le \sum_{b \in B} planned\_pax_{m,b} - min\_pax_m && \forall m \in M && \text{(J11)} \\
& \sum_{b \in B} ADD\_\mathrm{PAX}_{m,b} \le max\_pax_m - \sum_{b \in B} planned\_pax_{m,b} && \forall m \in M && \text{(J12)} \\
& \sum_{m \in M} ADD\_PAX_{m,b} - \sum_{m \in M} DOWN\_PAX_{m,b} + \sum_{m \in M} EXCESS\_PAX_{m,b} \le pool_b \\
& && \forall b \in B && \text{(J13)} \\
& 2 \sum_{\substack{m \in M, \\ v \in V}} \mathrm{PAX}_{m,\mathrm{v},a} \overset{\circ}{\ge} \sum_{\substack{m \in M, \\ b \in \mathrm{B}}} \mathrm{PAX}_{m,b,a} && \forall a \in A && \text{(J14)}
\end{aligned}
$$

$$2\sum_{v \in \mathrm{B}} \mathrm{PAX}_{m,\mathrm{v},a} \overset{\circ}{\geq} \sum_{b \in \mathrm{B}} \mathrm{PAX}_{m,b,a} \qquad \forall m \in M, a \in A \qquad \text{(J15)}$$

$$\sum_{m \in M} PAX_{m,\text{'master'},a} \overset{\circ}{\geq} 2 \qquad \forall a \in A \qquad \text{(J16)}$$

$$ASSIGN_{m,a} \in \{0,1\} \qquad \forall m \in M, a \in A$$

$$HVY_{q,a} \in \{0,1\} \qquad \forall q \in Q, a \in A$$

$$PAX_{m,b,a} \in \{0,1,2,\ldots\} \qquad \forall m \in M, b \in B, a \in A$$

$$0 \leq DOWN\_PAX_{m,b} \qquad \forall m \in M, b \in B$$

$$0 \leq ADD\_PAX_{m,b} \qquad \forall m \in M, b \in B$$

$$0 \leq EXCESS\_PAX_{m} \qquad \forall m \in M$$

$$0 \leq DOWN\_HVY \leq planned\_hvy - min\_hvy$$

$$0 \leq ADD\_HVY \leq max\_hvy \text{ - } planned\_hvy$$

$$0 \leq EXCESS\_HVY \qquad \text{(J17)}$$

The objective (J0) evaluates the desirability of a tactical crossload based on the Airborne Commander's minimum, planned, and maximum number assigned per sub-mission or heavy equipment. If the planned numbers cannot be met, the model adjusts the numbers of paratroopers and heavy equipment to maximally adhere to the Airborne Commander's intent.

Each constraint (J1) restricts a piece of heavy equipment to be loaded on one aircraft.

Constraint (J2) facilitates the flexibility of the number of heavy equipment items loaded, allowing the planned number to be reduced or supplemented at a respective cost or reward.

Each constraint (J3) allows a mission to be assigned to a given maximum number of aircraft.

Each constraint (J4) permits a piece of equipment to be loaded onto an aircraft only if that aircraft has been assigned the mission of that equipment.

Each constraint (J5) precludes assigning a pair of mutually exclusive sub-missions to an aircraft.

Each constraint (J6) limits the number of seat positions occupied on an aircraft.

Each constraint (J7) allows paratroopers assigned to a sub-mission to only be assigned to an aircraft that has also been assigned that sub-mission.

Each pair of constraints (J8)-(J9) restricts the maximum and minimum number of paratroopers that can be assigned from any mission to any one aircraft.

Each constraint (J10) accounts for the number of jumpers assigned to a mission by experience, and potentially increases or decreases the planned number.

Each constraint (J11) limits the decrease of jumpers from a planned mission to a given minimum, and each (J12) limits the increase of jumpers to a planned mission to a given maximum.

Each constraint (J13) balances the total number of jumpers with experience across all assignments and a pool of additional jumpers available but not yet assigned to any mission. Constraints (J10)-(J13) can be used to generate bump plans deviating from some base plan in the case that the numbers of seats or aircraft change (Brown, et al. 1997).

Each constraint (J14) requires at least one jumper with experience on each aircraft for every novice.

Each constraint (J15) requires at least one jumper with experience for every novice per each mission on an aircraft.

Each constraint (J16) requires two jumping jumpmasters on each aircraft. Constraint (J17) gives variable domains: binary, integer, or non-negative.

Constraints (J2), (J9), (J10), (J14), (J15), and (J16) contain un-shown elastic features in case of logical infeasibilities, and these logical variables appear in the objective (J0) with penalties. These help diagnose data problems, and should not appear in any successful solution.

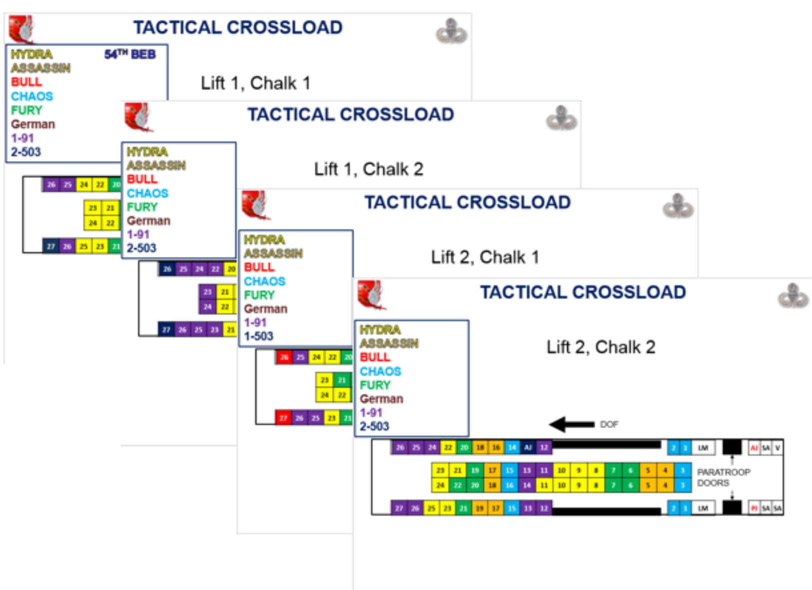
IV. TEST CASES, RESULTS, AND ANALYSIS

A. TEST CASES

We test TCP with two separate legacy airborne operations. One plan was created by the 4-319th Airborne Field Artillery Regiment (AFAR), Battalion level (see Figure 7); while the other was received from the 173rd Airborne Brigade Combat Team (ABN BCT), Brigade level.

To be clear, what we started with in each case was a complete legacy crossload plan, but what we needed was the operational problem for which this plan was an answer.

In order to test TCP with these two crossload problems, the author reverse-engineered each tactical crossload back to the inputs that planners would have used to create that tactical crossload (detailed data for all cases found in Appendix A). In the case of some data, such as priorities, some guesswork is required. TCP also has the ability to fix values of binary decision variables; this was not used for the test cases but can be found in Appendix B.



Graphical display of a typical tactical crossload created manually. Seats are color-coded to reflect the sub-mission of the paratrooper to be assigned to that seat. Each slide represents an aircraft in the airborne operation.

Figure 7. Legacy Tactical Crossload for 4-319th AFAR. Source: Pasquale (2017).

Each airborne mission consisted of two lifts—sorties of aircraft from load airfield across the dropzone and back—which the author separated. The separation is necessary because each lift uses the same aircraft. Once an aircraft from Lift 1 has dropped all PAX and equipment it returns to the departure airfield and takes on the PAX and equipment for Lift 2. Additionally, the required time to return from the dropzone to the departure airfield, reload PAX and equipment, and return to the dropzone, results in Lift 2 having completely different sub-missions than those from Lift 1. This results in the creation of four total different tactical crossloads.

Due to the difference in output from the legacy plans and the TCP, comparisons will be made on the distribution of sub-mission personnel across the aircraft participating in the airborne operation.

B. RESULTS

1. BN Level Operation

The typical airborne mission of an airborne artillery battalion revolves around dropping a howitzer, assembling at the gun, and providing indirect fire as soon as possible. Dropping an operational gun requires several different sections of paratroopers and, thus, the need for several sub-missions.

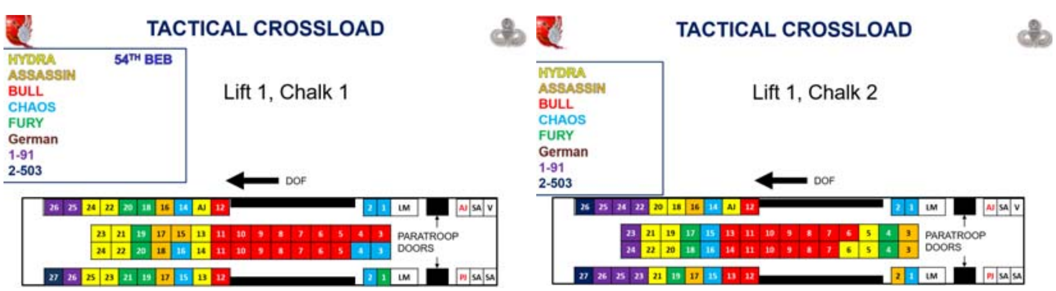
For Lift 1 in the 4-319 AFAR airborne mission there were nine sub-missions with a total of 111 PAX and two pieces of heavy equipment that occupied 12 seats each. Two aircraft were utilized for this operation and were filled to capacity. With the input of the reverse-engineered tactical crossload the TCP was able to produce a feasible alternative (see Figure 8).

```
C_130H_1
    m01
        novice              2
        experienced         3
    m04
        novice              9
        experienced         9
    m05
        novice              2
        experienced         2
    m06
        novice              1
        experienced         2
    m07
        novice              1
        experienced         1
        master              1
    m08
        novice              3
        experienced         3
    m09
        M119_Howitzer_2
        novice              2
        experienced         3
        master              1
    m10
        novice              1
        experienced         2
    m11
        novice              1
        experienced         3
    empty seats:        0

C_130H_2
    m01
        novice              1
        experienced         1
        master              1
    m02
        novice              1
        experienced         2
    m03
        novice              1
        experienced         2
    m04
        M119_Howitzer_1
        novice              3
        experienced         9
        master              4
    m05
        novice              1
        experienced         3
    m06
        novice              2
        experienced         2
    m07
        novice              2
        experienced         2
    m08
        experienced         2
        master              1
    m09
        novice              2
        experienced         2
        master              1
    m10
        novice              4
        experienced         3
        master              1
    empty seats:        0
```

Detailed breakdown by aircraft by the sub-missions by jumper experience level. Mission “m01” is split between the two aircraft, with two novice jumpers, and three experienced ones on the first aircraft, and one novice jumper, one experienced jumper, and one jumpmaster on the second aircraft. There is no empty seat on either aircraft. It is from this output that the subordinate commanders would allocate their personnel to seats.

Figure 8. TCP Output for Lift 1 4-319 AFAR



Depicts the legacy plan tactical crossload and is extremely similar to the crossload created by the TCP in Figure 5. There are differences, such as mission “m011” that is split zero and three by TCP and one and two in the legacy crossload.

Figure 9. Legacy Tactical Crossload for Lift 1 4-319 AFAR. Source: Pasquale (2017).

In comparing Figures 8 and 9 the similarities are clear. The legacy tactical crossload provided by 4-319th AFAR is a little more symmetric in its more-equal distribution of jumpers for sub-missions between the aircraft, but not significantly more so than the output of the TCP. For example, the very last mission in sequence, mission m11 is solely located on C-130H_1 in the legacy plan, while in the TCP tactical crossload it is split one and two, between C-130H_1 and C-130H_2.

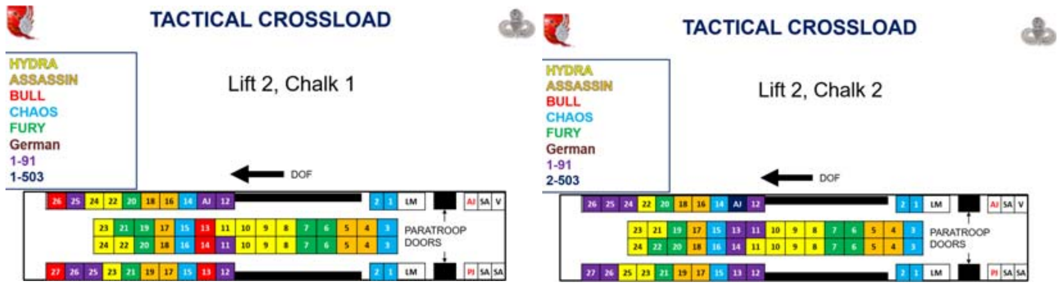
For Lift 2 in the 4-319 AFAR airborne mission there are 12 sub-missions with a total of 107 PAX and two pieces of heavy equipment that occupied 12 seats each. Two aircraft were utilized for this operation and were filled to capacity. With the input of the reverse-engineered legacy tactical crossload problem the TCP produced a feasible, optimal alternative (see Figure 10).

```
C_130H_1
         m01
              novice          2
              experienced     2
         m02
              novice          1
              experienced     1
         m03
              novice          1
              experienced     1
         m04
              M119_Howitzer_1
              novice          3
              experienced     3
         m05
              experienced     2
         m06
              experienced     3
         m07
              novice          2
              experienced     1
              master          1
         m08
              novice          4
              experienced     4
         m09
              M119_Howitzer_2
              experienced     4
         m10
              experienced     3
              master          1
         m11
              novice          1
              experienced     2
         empty seats:       0
```

```
C_130H_2
         m01
              novice          2
              experienced     4
              master          2
         m02
              novice          2
              experienced     3
              master          1
         m03
              novice          2
              experienced     3
              master          1
         m04
              novice          3
              experienced     3
              master          2
         m05
              novice          4
              experienced     4
         m07
              experienced     4
         m08
              experienced     4
         m09
              novice          3
              experienced     3
         m10
              novice          4
              experienced     4
         m11
              novice          2
              experienced     3
         m12
              experienced     2
         empty seats:       0
```

Tactical crossload created by the TCP that breaks down by aircraft by sub-mission by experience level. Mission “m01” is split between the two aircraft, two novice jumpers, and two experienced jumpers on the first aircraft, and two novice jumpers, four experienced jumpers, and two jumpmasters on the second. There is no empty seat on either aircraft. It is from this output that the subordinate commanders would allocate their personnel to seats.

Figure 10. TCP Output for Lift 2 4-319th AFAR



Depicts the legacy tactical crossload and is similar to the crossload created by the TCP in Figure 5. There are differences, such as mission "m01" that is split four and eight in TCP crossload and six and six in the legacy crossload.

Figure 11. Legacy Tactical Crossload for Lift 2 4-319th AFAR

As with Lift 1, the TCP created an extremely similar tactical crossload to that provided by the 4-319th AFAR (see Figures 10 and 11). Again the TCP tactical crossload is a little less symmetric (i.e., splitting numbers of jumpers for each mission between the aircraft more equally) but it is still an optimal solution.

For both lifts the TCP was able to produce tactical crossloads that are both optimal (with maximized objective function) and very similar to that of the legacy tactical crossloads executed by 4-319th AFAR. Both tactical crossloads have an optimal total score because they each load the heavy equipment items and avoid any penalty by violating any constraint. The TCP created each tactical crossload in a matter of moments.

2. BCT Level Operation

Upon careful examination of the 173rd legacy tactical crossload, Lift 1 appears to be a training jump rather than a tactical airborne operation. So Lift 1 will be excluded from the thesis results. Lift 2 is a significantly larger airborne operation than that of the 4-319th AFAR. Though Lift 2 consists of only eight sub-missions it requires 12 aircraft (four C-130J and eight C-130H) in order to convey 555 PAX.

```
C_130J_1
    m01
        experienced    22
    m02
        experienced    2
    m03
        novice         2
        experienced    5
    m04
        novice         11
        experienced    11
    m06
        master         2
    empty seats:       0
C_130J_2
    m01
        novice         11
        experienced    11
    m03
        novice         1
        master         1
    m04
        novice         11
        experienced    11
    m06
        novice         1
        master         1
    m07
        experienced    8
    empty seats:       0
C_130J_3
    m01
        novice         10
        experienced    11
    m04
        novice         11
        experienced    10
        master         1
    m06
        novice         2
        experienced    2
    m07
        novice         3
        experienced    3
    m08
        novice         1
        master         1
    empty seats:       0
C_130J_4
    m01
        experienced    4
        master         17
    m02
        experienced    2
    m04
        experienced    22
    m05
        experienced    2
    m06
        experienced    4
    m08
        novice         2
        experienced    2
    empty seats:       0
C_130H_1
    m01
        novice         5
        experienced    5
    m04
        experienced    22
    m05
        experienced    2
    m06
        novice         1
        experienced    1
    m07
        novice         1
        master         2
    m08
        novice         1
        experienced    1
    empty seats:       0
C_130H_2
    m01
        novice         5
        experienced    5
    m02
        novice         1
        experienced    1
    m04
        novice         11
        experienced    11
    m05
        experienced    2
    m06
        master         2
    m08
        experienced    3
    empty seats:       0
C_130H_3
    m01
        novice         11
        experienced    11
    m04
        master         2
    m06
        experienced    2
    m07
        novice         7
        experienced    7
    m08
        experienced    2
    empty seats:       0
C_130H_4
    m01
        novice         7
        experienced    7
    m04
        experienced    22
    m06
        novice         1
        master         1
    m07
        novice         1
        experienced    1
    m08
        experienced    1
        master         1
    empty seats:       0
C_130H_5
    m01
        novice         11
        experienced    11
    m02
        novice         1
        experienced    1
    m03
        novice         2
        experienced    2
    m04
        novice         6
        master         6
    m06
        experienced    2
    empty seats:       0
C_130H_6
    m01
        experienced    22
    m04
        novice         7
        experienced    5
        master         2
    m06
        experienced    2
    m07
        experienced    2
    m08
        novice         1
        experienced    1
    empty seats:       0
C_130H_7
    m01
        novice         9
        experienced    10
    m03
        novice         1
        experienced    1
    m04
        novice         6
        experienced    11
    m06
        master         2
    m07
        experienced    2
    empty seats:       0
C_130H_8
    m01
        novice         11
        experienced    11
    m03
        experienced    2
    m04
        novice         7
        experienced    5
        master         2
    m06
        experienced    2
    m07
        experienced    2
    empty seats:       0
```

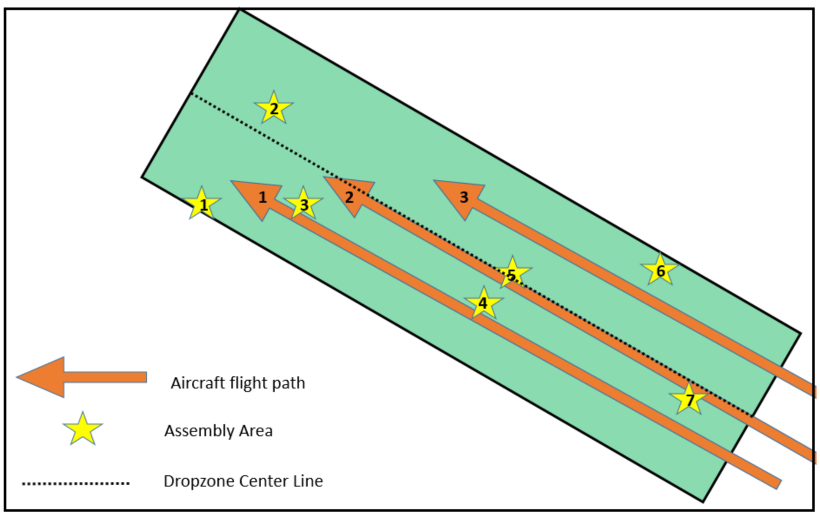
Tactical crossload created by the TCP that breaks down by aircraft by sub-mission by experience level. Mission "m01" is spread across all 12 aircraft with total PAX ranging from 10 to 22 PAX per aircraft. There is no empty seat on any aircraft.

Figure 12. TCP Output for 173rd ABN BCT

TCP produces an optimal solution in just over a half-second. As with the two Lifts from the 4-319th AFAR, the tactical crossload created by the TCP looks very similar to that of the legacy tactical crossload provided by 173rd ABN BCT. The key difference is that for mission "m04" on C-130H_3 there are only two PAX and in the legacy tactical crossload the lowest number of "m04" PAX assigned to an aircraft is 12.

3. Feature Testing

The 173rd ABN BCT tactical crossload exhibits pairwise mutually exclusive sub-missions that cannot be assigned to the same aircraft. There are two reasons that two missions cannot be assigned to the same aircraft. One is the close proximity of two AAs (see AAs 4 and 5 in Figure 13), which limits the ability of a single aircraft to deliver paratroopers close to both. Another reason is excessive distance between AAs perpendicular to the aircraft flight path (see AAs 1 and 6 in Figure 13). For example in Figure 13 sub-mission 6 should not be assigned to the number one aircraft, and likewise sub-mission 1 should not be assigned to the number three aircraft. In the typical aircraft formation, offset trail (see Figure 13), some aircraft will be significantly farther from some AAs than others and ensuring an aircraft does not carry elements assigned to both sub-missions limits the distance a paratrooper might have to cover on the ground.



Assembly Areas 4 and 5 would be considered mutually exclusive due to close proximity and Assembly Areas 1 and 6 would be considered mutually exclusive due to total distance opposite the dropzone center line.

Figure 13. Flight Paths across Dropzone

The original concept for bump plan creation was to simply re-execute TCP with the adjusted number of seats available. This approach has the benefit of creating an ideal scatter plan with the new information but depending on the time in which the bump plan is initiated can significantly delay the time on target for the entire airborne operation. The approach incorporated in the TCP is to limit the number of personnel affected by the bump plan therefore limiting the overall number of changes to the tactical crossload.

In order to demonstrate TCP generating a bump plan, we simulated the loss of 25 seats from a single aircraft from Lift 1 in the 4-319th AFAR airborne mission. Figure 14 shows how TCP removes paratroopers from the airborne mission in relation to the priority of the Airborne Commander determined by the provided data of low, planned and high PAX numbers.

```
jumper and pool reassignments
experience mssn change              PAX    reward
novice      before reassignments:    10 in unassigned pool
           m01  DOWN_PAX:            -1         -2
           m02  DOWN_PAX:            -1         -2
           m03  DOWN_PAX:            -1         -2
           m05  DOWN_PAX:            -1         -2
           m07  DOWN_PAX:            -2         -4
           m08  DOWN_PAX:            -3         -6
           m09  DOWN_PAX:            -5        -10
novice      after reassignments:     24 in unassigned pool
experienced before reassignments:    10 in unassigned pool
           m01  DOWN_PAX:            -1         -2
           m03  DOWN_PAX:            -1         -2
           m05  DOWN_PAX:            -1         -2
           m06  DOWN_PAX:            -1         -2
           m07  DOWN_PAX:            -1         -2
           m09  DOWN_PAX:            -2         -4
experienced after reassignments:     17 in unassigned pool
master      before reassignments:    10 in unassigned pool
           m03  DOWN_PAX:            -1         -2
           m09  DOWN_PAX:            -3         -6
master      after reassignments:     14 in unassigned pool

total change to reward function:        -50
```

Detailed list of paratroopers removed from airborne operation due to bump broken down by skill level and sub-mission. For example, mission "m01' loses a total of two PAX as a result of the bump plan, and this inflicts a penalty of four in the objective reward function.

Figure 14. Personnel Lost due to 4-319th AFAR Bump (TCP)

The losses are spread out between the relative mission sizes with the larger missions losing more PAX in order to maintain a relative loss rate across the different sub-missions (see figure 15). Further, the losses limit turbulence from the base plan (the number of changes required to the other aircraft in the Airborne Operation). Changes are only required on the aircraft that lost seats.

m	seq	min_pax	planned	max_pax
m01	1	5	8	12
m02	2	5	7	12
m03	3	7	10	15
m04	4	28	34	40
m05	5	5	8	15
m06	6	3	4	10
m07	7	5	9	15
m08	8	7	11	15
m09	9	10	20	25

Example of the mission data guiding the 4-319th bump plan in Figure 14. Shown is each mission identification, its sequence, and the minimum, ideal, and maximum numbers of PAX desired.

Figure 15. Airborne Commander PAX Inputs

Next we test the loss of a C-130H with 42 seats from the 163rd ABN BCT airborne mission. As evident in Figure 13, the TCP removes paratroopers from the airborne mission in relation to the priority of the Airborne Commander determined by the provided low, planned and high PAX numbers (Figure 16).

```
jumper and pool reassignments
experience mssn change              PAX    reward
novice      before reassignments:    10 in unassigned pool
           m01  DOWN_PAX:           -10       -20
           m03  DOWN_PAX:            -2        -4
           m04  DOWN_PAX:            -7       -14
           m06  DOWN_PAX:            -1        -2
           m07  DOWN_PAX:            -1        -2
novice      after reassignments:     31 in unassigned pool
experienced before reassignments:    10 in unassigned pool
           m01  DOWN_PAX:           -10       -20
           m03  DOWN_PAX:            -1        -2
           m04  DOWN_PAX:            -4        -8
           m06  DOWN_PAX:            -1        -2
           m07  DOWN_PAX:            -1        -2
           m08  DOWN_PAX:            -1        -2
experienced after reassignments:     28 in unassigned pool
master      before reassignments:    10 in unassigned pool
           m03  DOWN_PAX:            -1        -2
           m04  DOWN_PAX:            -2        -4
master      after reassignments:     13 in unassigned pool

total change to reward function:        -84
```

Detailed list of paratroopers removed from airborne operation due to 42 seats lost, broken down by skill level and sub-mission. For example, mission “m01’ loses a total of 20 PAX as a result of the bump plan, which inflicts a reward penalty of 40.

Figure 16. Personnel due to 173rd ABD BCT Bump (TCP)

With the loss of an entire aircraft the TCP still tries to minimize the number of alterations made to the overall tactical crossload and as such only two aircraft have their original crossload adjusted. This enables the Airborne Commander's intent to be accomplished while minimizing the number of changes.

C. ANALYSIS

Gen. George S. Patton famously said, "A good plan, violently executed now, is better than a perfect plan next week" (Patton, ca. 1943). Perfect plans take time. In conflict, time is a luxury, especially in airborne operations. It takes weeks to produce plans like those of the 173rd ABN BCT or the 4-319th AFAR. TCP takes less than a second to formulate the most time-consuming aspect of a plan for an airborne operation. Not only can the airborne operation be planned quicker, but the planners creating the crossload would be free to focus on other aspects of the operation.

Because only previously created legacy crossloads were available, the author was not able to test the ability to capture the intent of the actual commanders. By taking the completed legacy tactical crossload from the 4-319th AFAR and the 173 ABN BCT, no insight is gained beyond that of the final product and we have no recoverable concept of how the Airborne Commander would adjust the crossload given any addition of loss of seats. (I.e., we had to work with an answer, and guess the question.) Additionally, because the airborne missions have already taken place, there was no need to stress the capability to create a bump plan. In the two airborne missions discussed, only the 173rd mission had a published bump plan; though it is not uncommon that a battalion-sized airborne mission would fail to have a published bump plan owing to the small scale of the operation and the lack of personnel to plan and organize one.

Bump Plan Concept

Marking:
- Key personnel will be marked with green tape (personnel identified during Static Load Training).
- Bump personnel will be marked with masking tape (personnel identified during Static Load Training).
- All key personnel will carry 5 x bump cards in left breast pocket.

Chalk Guides:
- Chalk Guide teams will be attached to one aircraft throughout the entire exercise.
- Chalk Leaders' packets will contain bump and tactical cross load guidance for all days.
- In the event of the execution of a bump plan, Chalk Guides will work with the JM team to lead key personnel to their new chalks and remove bump personnel.

Bump by Phase:
1. Prior to Load: If an aircraft is scratched prior to load, the airborne commander may initiate a bump plan. Chalk Guides will escort key personnel from the chalk associated with a non-mission capable aircraft to their new chalk and secure their Bump Cards. Chalk Guides will escort bump personnel back to the PAHA.
2. Ramp side: If an aircraft incurs issues during pre-flight checks, the airborne commander may initiate a ramp side bump plan. Chalk Guides will escort key personnel off of the non-mission capable aircraft while removing bump personnel from the designated bump aircraft. Chalk Guides will secure Bump Cards of the key personnel and update the manifest with the MACO. The DACO, Chalk Guide and MACO are responsible for the successful execution of ramp side pax bumps.
3. Post-station time: The Airborne Commander is the approval authority for bumps executed post-station time. If a bump is not authorized, key personnel may be moved to another air movement the next day.

Vehicle Bumps by Phase:
1. Prior to Load: The Team Mobility OIC and the HE/CDS/Airland Team Lead will advise the Airborne Commander on the timeline implications of bumping a vehicle to another aircraft prior to load time. The Airborne Commander may choose to attempt a pre-load bump.
2. Rampside: The Team Mobility OIC and the HE/CDS/Airland Team lead will advise the Airborne Commander on the costs and benefits of bumping equipment to another aircraft past load time. The Airborne Commander may choose to attempt a post-load bump despite negative consequences to the timeline. Essential equipment may be bumped to the next day.
3. Post-station time: no same-day bump will be executed post-station time. Essential equipment will be bumped into the next day's airborne operation.

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As of 05APR16

Detailed Bump Plan published with the legacy tactical crossload for the 173rd ABN BCT airborne operation. Markings refer to an identifying strip of tape wrapped around a jumper's upper arm. Chalk guides are the Air Force personnel who escort a chalk to its assigned aircraft. The phases referenced in the bump plan are the time intervals of an airborne operation starting with arrival at the departure airfield and ending with aircraft take-off.

Figure 17. 173rd Published Bump Plan. Source: Pasquale (2017).

The 173rd Bump Plan (see Figure 17) is fairly complete in detailing how to execute the bump plan during the three different phases prior to aircraft take-off. At the earliest time, prior to load, there is little that the current bump plan accomplishes other than removing key personnel and placing them into new aircraft and removing the pre-assigned bump personnel, as detailed in Figure 17. This is a better plan than is typical, but it still lacks flexibility. For example, what if the whole aircraft is not scratched and only a handful of seats are inoperable; which personnel lose seats? What if more than one aircraft goes down and the sole bump plan is for the loss of only a single aircraft? In events such as these, the 173rd bump plan is flawed but still a feasible course of action.

However, a majority of airborne missions either have no such plan or lack the detail of the 173rd plan. A better method to create a bump plan is required. This thesis provides the ability to change the number of aircraft or the seats available on a given aircraft, and then create a revised plan in moments. After all the inputs are in the TCP, the creation of a bump plan is as easy as adjusting the aircraft information because the previous inputs by the airborne commander, the subordinate commanders and the airborne planners will not change.

The TCP introduced here adds an additional layer of sophistication by addressing the safety concern associated with the skill level of the individual paratrooper. Typically the assignment of the paratroopers is determined by the sub-mission level. It is entirely up to the sub-mission commander to decide where to allocate paratroopers. TCP provides guidance as to what skill level of paratrooper should be assigned to each seat. This enables the Airborne Commander’s intent to be fulfilled across the entire aircraft rather than just across each sub-mission. This provides sub-missions that may not have the appropriate spacing between novice jumpers to be supplemented by other sub-missions on the each respective aircraft.

V. CONCLUSION

A. CONCLUSIONS

This thesis presents an optimization model that automates a portion of the airborne operation planning. The tool takes inputs from the Airborne Commander, subordinate commanders, and the airborne planners to suggest a manifest for each aircraft taking part in the airborne operation. The optimization model is an integer linear program, an optimized assignment program that assigns seats across all aircraft participating in the airborne operation.

TCP takes a process that has traditionally taken days to weeks and automates it near instantaneously. Additionally, TCP can quickly create bump plans, which could prove critical in evolving airborne operations. Even if manual massaging of a TCP crossload plan is required, TCP quickly provides an initial plan that is fully consistent with all expressed inputs. That these inputs must be written out provides a valuable audit trail to explain why a crossload exhibits its detail.

The PYTHON implementation of TCP automatically extracts index sets and data files from a single, unified spreadsheet, and populates that same spreadsheet with the resulting crossload plan.

B. FUTURE WORK

An option for future work includes improving TCP to include items of special equipment. In airborne operations, paratroopers jump with their assigned weapon system, typically an M4 assault rifle. But, there are cases in which an M4 is not the assigned weapon. For example, some paratroopers jump with Stinger Missiles. There are additional safety regulations established in the ASOP to deal with this that are not taken into account in this thesis. Second, door bundles can be added. For some operations additional equipment is needed that is not suited for attachment to a paratrooper. This equipment is packaged and thrown out of the aircraft when first crossing the dropzone. While the door bundle does not require a seat allocation, it does require that the first jumper be a jumpmaster and, thus, capable of assisting either the primary jumpmaster or the alternate jumpmaster in deploying the door bundle.

Another embellishment would incorporate a model to project point-of-impact (POI) for each paratrooper in an attempt to minimize the required distance to reach the paratrooper's respective AA. The capability to deliver paratroopers as closely as possible to their respective AAs would increase the speed those paratroopers are then able to assemble and subsequently initiate movement.

Over the past several years there has been some effort devoted to developing an electronic manifest tool. An electronic manifest tool is based on scanning paratroopers' identification cards to populate a manifest. If the TCP developed in this thesis could be tied in with an electronic manifest tool, it would significantly aid in the creation of the paper manifest required for both the Air Force and basic accountability purposes.

DARPA has awarded a research contract to develop a tactical crossload tool.

> [C]omputer assisted Airborne Planning Application (APA) that provides a continuum of planning capability including import of background information, entry of tasking, entry and management of forces assigned, entry of Tactical Crossload from user inputs, animation of the plan rehearsal, export of briefing products, and automatic generation of DA Form 1306 manifests. The plan can be displayed in a view of each aircraft, a view of each manifest, and as an animation of anticipated landing time and location on a Geographic display. (Sheehan, 2017).

This thesis and accompanying files will be made available to any qualified contractor as well as the 82nd Airborne Division.

APPENDIX A. INPUTS

A. 4-319TH AFAR LIFT 1

Scalars Setting:

```
     minassign         /  3 /
     maxassign         / 18 /
     maxacpermission   / 10 /
     hvy_pri_lo        /  2 /
     hvy_pri_up        /  1 /
     min_hvy           /  2 /
     planned_hvy       /  2 /
     max_hvy           /  2 /
     reward4assigns    /  1 /
```

a.SET:

```
C_130H_1
C_130H_2
```

aircraft_data.csv:

```
a, seats
C_130H_1 ,65
C_130H_2 ,65
```

background_data.csv:

```
* b, pool(b)
   novice      ,  10
   experienced ,  10
   master      ,  10
```

heavy_data.csv:

```
q, equip_pri, seat_req
M119_Howitzer_1 ,100,12
M119_Howitzer_2,200,12
```

m.SET:

```
m01
m02
m03
m04
m05
m06
m07
m08
m09
```

```
m10
m11
heavy
```

mission_data.csv:

```
m, seq, min_pax, max_pax, pax_pri_lo, pax_pri_up
m01  ,1,5,12,2,1
m02  ,2,5,12,2,1
m03  ,3,7,15,2,1
m04  ,4,28,40,2,1
m05  ,5,5,15,2,1
m06  ,6,3,10,2,1
m07  ,7,5,15,2,1
m08  ,8,7,15,2,1
m09  ,9,10,25,2,1
```

planned_data.csv:

```
m, b, planned_pax
m01  , novice       ,3
m01  , experienced  ,4
m01  , master       ,1
m02  , novice       ,2
m02  , experienced  ,4
m02  , master       ,1
m03  , novice       ,4
m03  , experienced  ,5
m03  , master       ,1
m04  , novice       ,12
m04  , experienced  ,18
m04  , master       ,4
m05  , novice       ,3
m05  , experienced  ,5
m05  , master       ,0
m06  , novice       ,1
m06  , experienced  ,3
m06  , master       ,0
m07  , novice       ,3
m07  , experienced  ,5
m07  , master       ,1
m08  , novice       ,4
m08  , experienced  ,5
m08  , master       ,2
m09  , novice       ,5
m09  , experienced  ,12
m09  , master       ,3
```

q.SET:
```
M119_Howitzer_1
M119_Howitzer_2
```

qm.SET:
```
* q, m
M119_Howitzer_1 , m04
M119_Howitzer_2 , m09
```

B. 4-319TH AFAR LIFT 1 BUMP

Scalars Setting:
```
     minassign          /  3 /
     maxassign          / 18 /
     maxacpermission    / 10 /
     hvy_pri_lo         /  2 /
     hvy_pri_up         /  1 /
     min_hvy            /  2 /
     planned_hvy        /  2 /
     max_hvy            /  2 /
     reward4assigns     /  1 /
```

a.SET:
```
C_130H_1
C_130H_2
```

aircraft_data.csv:
```
a, seats
C_130H_1 ,65
C_130H_2 ,45
```

background_data.csv:
```
* b, pool(b)
   novice      ,  10
   experienced ,  10
   master      ,  10
```

heavy_data.csv:
```
q, equip_pri, seat_req
M119_Howitzer_1 ,100,12
M119_Howitzer_2,200,12
```

m.SET:
```
m01
m02
```

```
m03
m04
m05
m06
m07
m08
m09
m10
m11
heavy
```

mission_data.csv:

```
m, seq, min_pax, max_pax, pax_pri_lo, pax_pri_up
m01  ,1,5,12,2,1
m02  ,2,5,12,2,1
m03  ,3,7,15,2,1
m04  ,4,28,40,2,1
m05  ,5,5,15,2,1
m06  ,6,3,10,2,1
m07  ,7,5,15,2,1
m08  ,8,7,15,2,1
m09  ,9,10,25,2,1
```

planned_data.csv:

```
m, b, planned_pax
m01  , novice       ,3
m01  , experienced  ,4
m01  , master       ,1
m02  , novice       ,2
m02  , experienced  ,4
m02  , master       ,1
m03  , novice       ,4
m03  , experienced  ,5
m03  , master       ,1
m04  , novice       ,12
m04  , experienced  ,18
m04  , master       ,4
m05  , novice       ,3
m05  , experienced  ,5
m05  , master       ,0
m06  , novice       ,1
m06  , experienced  ,3
m06  , master       ,0
m07  , novice       ,3
m07  , experienced  ,5
m07  , master       ,1
```

```
m08  , novice       ,4
m08  , experienced  ,5
m08  , master       ,2
m09  , novice       ,5
m09  , experienced  ,12
m09  , master       ,3
```

q.SET:

```
M119_Howitzer_1
M119_Howitzer_2
```

qm.SET:

```
* q, m
M119_Howitzer_1 , m04
M119_Howitzer_2 , m09
```

**C.	4-319TH AFAR LIFT 2**

Scalars Setting:

```
   minassign         /  2 /
   maxassign         / 8 /
   maxacpermission   / 10 /
   hvy_pri_lo        /  2 /
   hvy_pri_up        /  1 /
   min_hvy           /  2 /
   planned_hvy       /  2 /
   max_hvy           /  2 /
   reward4assigns    /  1 /
```

a.SET:

```
C_130H_1
C_130H_2
```

aircraft_data.csv:

```
a, seats
C_130H_1, 66
C_130H_2 ,65
```

background_data.csv:

```
* b, pool(b)
   novice      ,  10
   experienced ,  10
   master      ,  10
```

heavy_data.csv:

```
q, equip_pri, seat_req
```

```
M119_Howitzer_1 ,100,12
M119_Howitzer_2,200,12
```

m.SET:

```
m01
m02
m03
m04
m05
m06
m07
m08
m09
m10
m11
m12
heavy
```

mission_data.csv:

```
m, seq, min_pax, max_pax, pax_pri_lo, pax_pri_up
m01  ,1,7,15,2,1
m02  ,2,5,15,2,1
m03  ,3,5,15,2,1
m04  ,4,10,20,2,1
m05  ,5,5,15,2,1
m06  ,6,2,6,2,1
m07  ,7,5,15,2,1
m08  ,8,7,15,2,1
m09  ,9,7,15,2,1
m10  ,10,7,15,2,1
m11,11,5,12,2,1
m12,12,1,5,2,1
```

planned_data.csv:

```
m, b, planned_pax
m01  , novice       ,4
m01  , experienced  ,6
m01  , master       ,2
m02  , novice       ,3
m02  , experienced  ,4
m02  , master       ,1
m03  , novice       ,3
m03  , experienced  ,4
m03  , master       ,1
m04  , novice       ,6
m04  , experienced  ,6
```

```
m04  , master       ,2
m05  , novice       ,4
m05  , experienced  ,6
m05  , master       ,0
m06  , novice       ,0
m06  , experienced  ,3
m06  , master       ,0
m07  , novice       ,2
m07  , experienced  ,5
m07  , master       ,1
m08  , novice       ,4
m08  , experienced  ,8
m08  , master       ,0
m09  , novice       ,3
m09  , experienced  ,7
m09  , master       ,0
m10  , novice       ,4
m10  , experienced  ,7
m10  , master       ,1
m11, novice       ,3
m11, experienced  ,5
m11, master       ,0
m12, novice       ,0
m12, experienced  ,2
m12, master       ,0
```

q.SET:

```
M119_Howitzer_1
M119_Howitzer_2
```

qm.SET:

```
* q, m
M119_Howitzer_1 , m04
M119_Howitzer_2 , m09
```

D. 173RD ABN BCT

Scalars Setting:

```
   minassign         /  2 /
   maxassign         / 22 /
   maxacpermission   / 12 /
   hvy_pri_lo        /  2 /
   hvy_pri_up        /  1 /
   min_hvy           /  1 /
```

```
   planned_hvy       /  1 /
   max_hvy           /  1 /
   reward4assigns    /  1 /
```

a.SET:

```
C_130J_1
C_130J_2
C_130J_3
C_130J_4
C_130H_1
C_130H_2
C_130H_3
C_130H_4
C_130H_5
C_130H_6
C_130H_7
C_130H_8
```

aircraft_data.csv:

```
a, seats
C_130J_1,55
C_130J_2,56
C_130J_3,55
C_130J_4,55
C_130H_1,41
C_130H_2,41
C_130H_3,42
C_130H_4,42
C_130H_5,42
C_130H_6,42
C_130H_7,42
C_130H_8,42
```

background_data.csv:

```
* b, pool(b)
   novice      ,  10
   experienced ,  10
   master      ,  10
```

heavy_data.csv:

```
q, equip_pri, seat_req
Fill,100,0
```

m.SET:

```
m01
m02
```

```
m03
m04
m05
m06
m07
m08
heavy
```

MEX.SET

```
m02, m07
m03, m08
```

mission_data.csv:

```
m, seq, min_pax, max_pax, pax_pri_lo, pax_pri_up
m01  ,1,200,250,2,1
m02  ,2,5,12,2,1
m03  ,3,12,22,2,1
m04  ,4,200,225,2,1
m05  ,5,3,12,2,1
m06  ,6,20,35,2,1
m07  ,7,30,50,2,1
m08  ,8,12,25,2,1
```

planned_data.csv:

```
m, b, planned_pax
m01  , novice       ,80
m01  , experienced  ,130
m01  , master       ,17
m02  , novice       ,2
m02  , experienced  ,6
m02  , master       ,0
m03  , novice       ,6
m03  , experienced  ,10
m03  , master       ,1
m04  , novice       ,70
m04  , experienced  ,130
m04  , master       ,13
m05  , novice       ,0
m05  , experienced  ,6
m05  , master       ,0
m06  , novice       ,5
m06  , experienced  ,15
m06  , master       ,8
m07  , novice       ,12
m07  , experienced  ,25
m07  , master       ,2
```

```
m08  , novice      ,5
m08  , experienced ,10
m08  , master      ,2
```

q.SET:

```
Fill
```

qm.SET:

```
* q, m
Fill, m01
```

E. 173RD ABN BCT BUMP

Scalars Setting:

```
   minassign        /  2 /
   maxassign        / 22 /
   maxacpermission  / 12 /
   hvy_pri_lo       /  2 /
   hvy_pri_up       /  1 /
   min_hvy          /  1 /
   planned_hvy      /  1 /
   max_hvy          /  1 /
   reward4assigns   /  1 /
```

a.SET:

```
C_130J_1
C_130J_2
C_130J_3
C_130J_4
C_130H_1
C_130H_2
C_130H_3
C_130H_4
C_130H_5
C_130H_6
C_130H_7
C_130H_8
```

aircraft_data.csv:

```
a, seats
C_130J_1,55
C_130J_2,56
C_130J_3,55
C_130J_4,55
C_130H_1,41
C_130H_2,41
```

```
C_130H_3,42
C_130H_4,42
C_130H_5,42
C_130H_6,42
C_130H_7,42
```

background_data.csv:

```
* b, pool(b)
   novice      ,  10
   experienced ,  10
   master      ,  10
```

heavy_data.csv:

```
q, equip_pri, seat_req
Fill,100,0
```

m.SET:

```
m01
m02
m03
m04
m05
m06
m07
m08
heavy
```

MEX.SET

```
m02, m07
m03, m08
```

mission_data.csv:

```
m, seq, min_pax, max_pax, pax_pri_lo, pax_pri_up
m01  ,1,200,250,2,1
m02  ,2,5,12,2,1
m03  ,3,12,22,2,1
m04  ,4,200,225,2,1
m05  ,5,3,12,2,1
m06  ,6,20,35,2,1
m07  ,7,30,50,2,1
m08  ,8,12,25,2,1
```

planned_data.csv:

```
m, b, planned_pax
m01  , novice       ,80
m01  , experienced  ,130
```

```
m01  , master       ,17
m02  , novice       ,2
m02  , experienced  ,6
m02  , master       ,0
m03  , novice       ,6
m03  , experienced  ,10
m03  , master       ,1
m04  , novice       ,70
m04  , experienced  ,130
m04  , master       ,13
m05  , novice       ,0
m05  , experienced  ,6
m05  , master       ,0
m06  , novice       ,5
m06  , experienced  ,15
m06  , master       ,8
m07  , novice       ,12
m07  , experienced  ,25
m07  , master       ,2
m08  , novice       ,5
m08  , experienced  ,10
m08  , master       ,2
```

q.SET:

```
Fill
```

qm.SET:

```
* q, m
Fill, m01
```

APPENDIX B. FIXING FILES

A decision support system that cannot be controlled by a planner will never be used. Accordingly, TCP accommodates three additional input files that enable a planner to optionally control any aspect of a crossload solution. Any solution detail can be controlled, and the remaining optimization continues conditional on these restrictions. Optionally, an entire crossload plan can be completely fixed for comparative analysis with alternative suggested solutions.

These three files respectively (and optionally) fix selected binary values of decision variables ASSIGN (mission to aircraft) and HVY (equipment to aircraft), and general integer variables PAX (for mission, by background, to aircraft). These are the only independent variables in our linear integer optimization model. All other variables are dependent on these decision variables (some would casually call these others passenger, or bookkeeping variables).

assign_fix.csv:

```
* assign_fix(m,a,binary_fix)
*   m01 , C_17_1, no  { yes or no fixes the assignment for
this mission m and aircraft a }
```

heavy_fix.csv:

```
* hvy_fix(q,a,binary_fix)
* M998_2 , C_17_3 , no  { yes or no fixes the assignment
for this mission m and heavy equipment q }
```

pax_fix.csv:

```
* TABLE pax_fix(m,b,a,limit,value)
m,b,a,limit,limit_value
* m01 , experienced , C_17_2 , lo , 16  { lo, up, fx to
numerical limit given }
  m01 , experienced , C_130H_1  , lo , 0
```

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